A model to predict the performance of roadheaders based on the Rock Mass Brittleness Index

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Synopsis

Roadheaders are very versatile excavation machines used in tunnelling, mine development, and mine production for soft to medium strength rock formations. Performance prediction is an important factor for successful roadheader application and generally deals with machine selection, production rate and bit consumption. Among many different parameters, brittleness is also one of the material properties related to breakage characteristics and can be used as a cuttability parameter from a mechanical excavation point of view. The main objective of the research study is to contribute the brittleness of rock excavated to construct a new empirical equation for predicting the performance of roadheaders in different material and operational conditions. In this regard, a new performance prediction model for medium duty roadheaders based on a brittleness index (BI) is presented. In this study, rock mass brittleness index (RMBI) is defined in order to investigate the influence of BI on roadheader performance. RMBI is an index which can be used to relate the intact and rock mass characteristics to machine performance. Results demonstrated that RMBI is highly correlated to instantaneous cutting rate (ICR) (R^2=0.94). Moreover, through the further analysis and normalization, the pick consumption index (PCI) was introduced as a parameter having a good relation with pick or bit consumption rates (PCR) (R^2=0.79). Finally, the new predictive models for ICR and PCR showed very good correlations with the actual measured values.

Keywords
Performance prediction, roadheader, brittleness index, mechanical excavation.

Introduction

Global trends, environmental restrictions, and other market conditions forced, in the last decade, mining companies all over the world to be more profitable and competitive. One of the ways to be more profitable operations is to use mechanical miners, such as roadheaders, continuous miners, impact hammers and tunnel boring machines, for ore extraction and excavation of development drivages. Since these miners allow for continuous operation, it is expected that mechanization of mines with mechanical miners would increase productivity, decrease production cost and improve competitiveness, which can lead to move away from the conventional drill and blast method. Roadheaders are a unique class of mechanical excavation machines that break rock by utilizing tungsten carbide tipped cutting tools laced in a specific geometry on a rotating cutting head. Roadheaders were first introduced and developed for mechanical excavation of coal in Hungary in the early 50s, are the extensively used partial-face excavators in the mining industry particularly in coal mining and industrial minerals. Roadheaders are very versatile excavation machines used in tunnelling, mine development, and mine production for soft to medium strength rock formations. They are favoured in mining operation due to a high degree of mobility, flexible cutting profile (i.e., horseshoe), and selective mining, providing immediate access to the face and the capability to cut medium rocks with a compressive strength of up to about 100 MPa[1]. In civil construction, they find wide use for excavation of tunnels (railway, roadway, sewer, diversion tunnels, etc.) in soft ground conditions, as well as for enlargement and rehabilitation of various underground structures. Their ability to excavate almost any profile opening also makes them very attractive to those mining and civil construction projects where various opening sizes and profiles need to be constructed. Other advantages such as low capital costs also make use of these machines more desirable for contractors.

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Performance prediction is an important issue for successful roadheader application and generally deals with machine selection, production rate and bit consumption. Performance prediction encompasses the assessment of instantaneous cutting rate (ICR), bit consumption rates and machine utilization for different geological units. The instantaneous cutting rate (ICR) is the production rate during actual cutting time (tons or m^3/cutting hour). Bit or pick consumption rate refers to the number of picks changed per unit volume or weight of rock excavated (picks/m^3 or m^3/pick). Machine utilization is the percentage of time used for excavation during the project. The roadheader production rate and pick consumption are controlled by several parameters including[2]:

- Rock parameters, such as rock compressive and tensile strength, per cent of hard and abrasive mineral content (i.e. quartz), rock fabric and matrix type and hardness, existence of orientated mechanical properties in the mineral composite, and elastic behaviour of rock material.
- Ground conditions, such as degree of jointing (RQD), joint conditions, groundwater, fault zones, mixed face situations, and overall rock mass class and support requirements.
- Machine specification, including machine weight, cutter head power, sumping, arcing, lifting, and lowering forces, cutter head type (axial or transverse), bit type, size, and other characteristics, number of allocation of bits on the cutter head, and the capacity of the back-up system.
- Operational parameters, such as shape, size, and length of opening, inclination, turns or cross-cuts, sequence of cutting and enlargement operation, number of rock formations in the tunnelling path, ground support method, and work schedule meaning number of shifts per day and days per week, etc.

A combination of these parameters determines the production rate of a given machine in a certain rock formation and ground condition. A full account of parameters affecting roadheader performance and methods for production estimates is given in Neil[3]. Among these parameters, there are some that cannot be controlled, including the rock and ground conditions as well as some operational parameters and, therefore, only machine parameters are under control for a particular tunnelling project. Normally, the first step is to determine whether roadheaders are feasible and can work with a reasonable production rate under a given situation. The second step is to select the class and general specifications of machine to be considered for the job among the machines available in the market. The third step is to match the current machine characteristics to the rock and ground conditions at hand to maximize its production rate. This can be accomplished through a study of design parameters and design optimization practice. Also, there have been numerous studies on possible modifications to achieve higher production rates when utilizing roadheaders. On the other hand, the rock strength limit for roadheaders has been constantly challenged due to the need for a mobile hard rock excavator in the industry[2].

A brief background of methods for roadheader performance prediction

Sandbak (1985) and Douglas (1985) used a rock classification system to explain the changes of roadheader advance rates at San Manuel Copper Mine in an inclined drift at an 11% grade[4–5]. Also, Bilgin *et al.* (2004) investigated the factors affecting the performance of a roadheader in an inclined tunnel (9° grade) but it is evident that the majority of performance prediction models were developed for horizontal or low dip tunnels[6]. Models for widely jointed rock formations were described by Uehigashi *et al.* (1987) , Schneider (1988), Gehring (1989), Dun *et al.* (1997) and Thuro and Plinninger (1998, 1999). They reported that for a given cutting power, cutting rates of roadheaders decreased dramatically with increasing values of rock compressive strength[7–12]. Copur *et al.* (1997, 1998) stated that if the power and the weight of the roadheaders were considered together, in addition to rock compressive strength, the cutting rate predictions were more realistic[1,13].

Another concept of predicting the machine instantaneous cutting rate was to use specific energy described as the energy spent to excavate a unit volume of rock material. Farmer and Garrity (1987) and Poole (1987) showed that for a given power of roadheader, the excavation rate in m^3/cutting hour might be predicted using specific energy values given as in the following equation[14–15]:

$$SE = \sigma_c^2 / 2E \quad [1]$$

where SE is the specific energy, σ_c is the rock compressive strength and E is the rock elastic modulus. Widely accepted rock classification and assessment for the performance estimation of roadheaders is based on the specific energy found from core cutting tests[16–18]. Detailed laboratory and *in situ* investigations carried out by McFeat-Smith and Fowell (1977, 1979) showed that there was a close relationship between specific energy values obtained from core cutting tests and cutting rates for medium and heavy weight roadheaders separately. They reported also that tool consumption might be predicted from weight loss of cutter used in core cutting test[16–17]. Rock cuttability classification based on a core cutting test is usually criticized because the effect of rock discontinuities are not reflected in performance prediction. Bilgin *et al.* (1988, 1990, 1996, 1997) developed a performance equation based on rock compressive strength and rock quality designation as given below[19–22]:

$$ICR = 0.28 \times P \times (0.974)^{RMCI} \quad [2]$$

$$RMCI = \sigma_C \times (RQD/100)^{2/3} \quad [3]$$

where ICR is the instantaneous cutting rate in m^3/cutting hour, P is the power of cutting head in hp, $RMCI$ is the rock mass cuttability index, σ_c is the uniaxial compressive strength in MPa, and RQD is the rock quality designation in per cent. One of the most accepted methods to predict the cutting rate of any excavating machine is to use cutting power, specific energy obtained from full-scale cutting tests and energy transfer ratio from the cutting head to the rock formation as in the following equation[2,23]:

$$ICR = k \frac{P}{SE_{opt}} \quad [4]$$

where *ICR* is the instantaneous production rate in m³/cutting hour, *P* is the cutting power of the mechanical miner in kW, SE_{opt} is the optimum specific energy in kWh/m³ and *k* is energy transfer coefficient depending on the mechanical miner utilized. Rostami *et al.* (1994) strongly emphasized that the predicted value of the cutting rate was more realistic if specific energy value in the equation was obtained from full-scale linear cutting tests in optimum conditions using real-life cutters. Rostami *et al.* (1994) pointed out that *k* changed between 0.45 and 0.55 for roadheaders and from 0.85 to 0.90 for TBMs[2].

The influence of brittleness index on rock cutting performance

Brittleness is commonly considered as one of the most crucial mechanical properties of rock. A general law for brittleness is that a more brittle rock breaks at very little deformation. Cuttability of rocks means resistance to cutting by mechanical tools such as pick cutters and roller cutters. The cuttability can be measured by full-scale linear cutting tests, and some index tests requiring core samples, such as small-scale cutting tests, indentation tests, uniaxial compressive strength tests, Brazilian tensile strength tests, point load tests, etc.[16,24]. Based on these tests, the specific energy, optimum cutting geometry, and forces acting on cutters are measured and/or predicted. Knowing these parameters helps selecting and designing mechanical miners and predicting their performance, which is used for feasibility and planning purposes[16,24–25]. A full-scale rock cutting test is one of the best tools for defining cuttability of rocks, since an actual rock sample is cut by a real-life cutter, which reduces the scaling effect. Its disadvantage is that it requires large blocks of rock samples (around 1x1x0.6 m), which are usually difficult, too expensive or impossible to obtain. Therefore, a core sample based cuttability tests are preferred in many cases, even though their predictive abilities are lower than full-scale rock cutting tests. Developing new index tests or test interpretation methods would improve the predictive abilities of core-based cuttability tests.

Brittleness is one of the material properties related to breakage characteristics under different loading conditions. Therefore, the brittleness can be used as a cuttability parameter[26–29]. Different measures of brittleness in rock mechanics have been developed for different purposes. Elongation, fracture failure, formation of fines, ratio of compressive to tensile strength, and angle of internal friction are some examples of measures of rock brittleness[30]. A limited number of researchers tried to use these conventional measures of rock brittleness to correlate with mechanical rock breakage efficiency or rock cutting performance, but the results were not satisfactory[26,30]. A common opinion of those researchers was that a brittleness concept relevant to mechanical excavation of rocks had to be developed.

A group of researchers developed a brittleness test to use as one of the predictive parameters for tunnel boring machine performance. Another group of researchers investigated brittle and ductile failure modes by triaxial testing and connected this information to rock cutting[31–32]. Another group of researchers indicated that the performances of tunnel boring machines and rotary drills were related to the ratio of rock uniaxial compressive strength and Brazilian tensile strength[27]. At present, different approaches (i.e., strain based, energy based, strength ratio, Mohr's envelop and special test) have been conducted for computing the brittleness; however, the measurement of brittleness has not standardized yet. Different definitions of brittleness, Equations [5] and [6], are summarized by Hucka and Das (1974)[30]. Altindag (2002) suggested a brittleness index that is obtained as function of uniaxial compressive strength and Brazilian tensile strength of rock (Equation [7])[33]. The brittleness is often computed by using Brazilian tensile and uniaxial compressive strength of rock in engineering practices[27,33–35]. The following three strength-based equations are widely utilized to determine brittleness indirectly:

$$BI1 = \frac{(\sigma_c - \sigma_t)}{(\sigma_c + \sigma_t)} \qquad [5]$$

$$BI2 = \frac{\sigma_c}{\sigma_t} \qquad [6]$$

$$BI3 = \frac{\sigma_c \cdot \sigma_t}{2} \qquad [7]$$

where *BI*1, *BI*2 and *BI*3 are brittleness indices, and σ_c and σ_t are uniaxial compressive strength and Brazilian tensile strength of rock, respectively. The effect of brittleness on roadheader performance has not been investigated in previous research works. The main objective of the research study described in this paper is to contribute the brittleness of rock excavated to develop a new performance prediction model in different material and operational conditions of roadheaders. In this regard, the Tabas coal mine project, the largest fully mechanized coal mine in Iran, is chosen for investigation. There are 4 DOSCO MD1100 roadheaders working to excavate the main drift galleries and development entries. Detailed *in situ* observations and data collection of machine performance and rock formations are made during the tunnels' excavation.

Tabas coal mine project

Tabas coal mine, the largest and unique fully mechanized coal mine in Iran, is located in the central part of Iran near the city of Tabas in Yazd province and situated 75 km from southern Tabas. The mine area is a part of Tabas-Kerman coalfield. The coalfield is divided into 3 parts in which the Parvadeh region, with the extent of 1200 km² and 1.1 billion tons of estimated coal reserve, is the biggest and main part to continue excavation and fulfilment for future years. The coal seam has eastern-western expansion with a reducing trend in thickness toward the east. Its thickness ranges from 0.5 to 2.2 m but in the majority of conditions it has a consistent 1.8 m thickness. Room and pillar and longwall mining methods are considered as the main excavation methods in the mine. The use of roadheaders in the Tabas coal mine project was a consequence of mechanization of the work. Coal mining by the longwall method with powered roof supports makes rapid advance of the access roads necessary. On the other hand, the two alternatives for mining very thick coal seams, i.e. room and pillar and longwall in flat seams, also makes the use of roadheader driving galleries in the coal seams necessary. Four DOSCO MD 1100 roadheaders of 34 t in weight, with a 82 kW axial cutting head are mainly used in driving galleries with soft (coal) to medium hard rock (siltstone and mudstone) in the Tabas coal mine. The basic specifications of the DOSCO MD 1100 roadheader are shown in Table I[36].

During the period of excavation, related field data, including machine performance and geotechnical parameters, were gathered and recorded by the authors to establish a database for a performance study of the aforementioned roadheaders. The performance of the roadheader, including instantaneous cutting rate and bit or pick consumption for the different zones in the tunnel route, was continuously recorded under highly controlled condition. Table II shows these results and properties.

Geotechnical properties of rock formation

The most important characteristics of the rock mass encountered in driving galleries are low strength and jointed rock formations. Field investigations were carried out in order to determine the structural characteristics of the rocks. Figure 1 shows the typical rock formations encountered in the tunnels' route. Laboratory investigations were also performed in accordance with ISRM suggested methods, in order to determine the geotechnical properties of rocks (Table II). In the majority of cases, the sequence of bedding layers in each cross-section were similar; hence, representative characteristics were considered for excavated material in each cross-section.

Table I

Typical specifications of DOSCO MD 1100 roadheaders[36]

Machine weight (base machine)	34 tons
Total power (standard machine)	From 157 kW
Power on cutting boom (standard machine)	82 kW axial, 112 kW transverse
Hydraulic system working pressure	140 bar
Tracking speeds – sumping/flitting	0.038/0.12 m/s
Ground pressure	1.4 kg/cm²
Machine length	8060 mm
Machine width	3000 mm
Machine height	1700 mm

Table II

Summary of rock properties and roadheader performance in different zones

Case no.	Representative uniaxial compressive strength (MPa)	Representative Brazilian tensile strength (MPa)	RQD (%)	Cutting duration (min)	Cutting volume (m³)	Instantaneous cutting rate (m³/h)	Pick (bit) consumption rate (m³/pick)
1	15	4	19	60	22.428	22.4	60.4
2	15	4	19	54	22.752	25.3	56.5
3	15	4	20	54	22.284	24.8	58.8
4	15	4	19	56	22.248	23.8	53.0
5	15	4	19	57	22.176	23.3	57.3
6	15	4	19	59	22.212	22.6	55.7
7	16	4	20	50	22.536	27.0	54.0
8	14	4	20	50	21.384	25.7	68.3
9	16	4	18	52	22.284	25.7	44.7
10	15	4	18	67	22.572	20.2	50.5
11	17	4	20	49	23.184	28.4	45.7
12	14	4	19	56	22.896	24.5	59.3
13	16	4	19	50	22.104	26.5	52.9
14	17	4	20	52	22.140	25.5	48.8
15	24	5	27	32	22.212	41.6	35.7
16	27	5	28	30	22.788	45.6	28.1
17	20	5	23	42	22.464	32.1	39.5
18	14	6	19	77	21.528	16.8	69.9
19	15	6	20	77	22.356	17.4	61.3
20	14	6	19	76	21.528	17.0	64.8
21	15	6	18	79	22.572	17.1	57.7
22	15	6	19	76	22.248	17.6	57.4
23	16	6	19	79	22.140	16.8	54.0
24	16	6	18	76	21.096	16.7	43.5
25	15	6	19	82	22.068	16.1	57.0
26	15	6	19	76	22.320	17.6	62.6
27	15	6	19	82	21.996	16.1	55.9
28	15	6	19	81	22.698	16.8	51.7
29	14	6	19	86	20.952	14.6	60.9
30	16	6	20	69	22.032	19.2	55.5
31	14	6	18	83	24.640	17.8	56.9
32	15	6	19	84	22.068	15.8	61.1
33	17	6	20	73	22.680	18.6	47.7
34	16	6	19	76	21.42	16.9	53.3
35	16	6	20	74	22.500	18.2	55.5
36	16	4	21	55	24.254	26.5	61.7
37	17	4	22	57	23.916	25.2	59.3
38	17	4	22	50	23.686	28.4	55.9
39	17	4	21	55	23.114	25.2	52.3
40	19	5	24	43	21.229	29.6	48.4
41	15	4	19	62	23.090	22.3	60.7

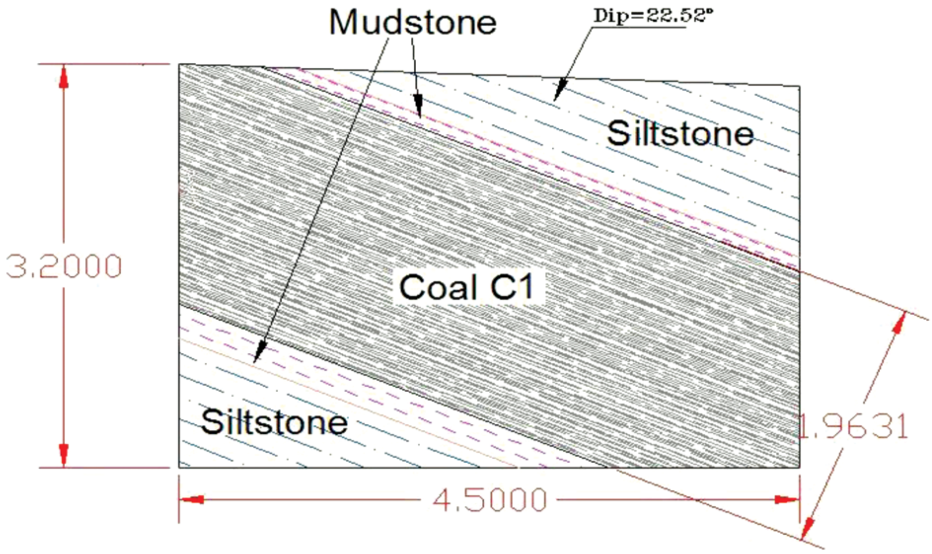

Figure 1—Typical view of rock formations encountered in the tunnels' route

Model construction to predict the performance of the roadheader

In rock engineering practices, the statistical based empirical equations have extensively been used to predict a required parameter from some simple tests or available collected data. The empirical equations have great importance during the early stages of rock excavation and design works since this is a more practical way as compared to extensive and expensive experimental programs.

In this study, in order to perform the statistical analyses for predicting the roadheader performance, a database of instantaneous cutting rate (ICR), pick consumption rate (PCR), uniaxial compressive strength (UCS), brazilian tensile strength (BTS) and rock quality designation (RQD) in different zones of excavation route was established (Table II). After the establishment of the database, statistical analysis was used to investigate the relation between machine and rock parameters.

Effect of encountered rock properties on roadheader performance

As a part of the study, to obtain the correlations between rock properties (UCS, BTS) and measured ICR, statistical analyses were carried out and the influence of each above-mentioned properties on the ICR were investigated. For statistical analysis, one of the commercial software packages for standard statistical analysis (SPSS) was used to perform the variable regression analysis between known parameters to investigate unknowns. The relationship between the UCS of rock with the ICR was found to be relatively good with a correlation coefficient (R^2) of 0.71, as demonstrated in Figure 2. Although the relationship seems to be relatively good, as seen in Figure 2, ICR increases as UCS of the rock increases. This is contrary to the previous results achieved from other studies; hence, it is necessary to consider rock mass properties to obtain reliable and realistic results. The relationship between the BTS of the rock with the ICR showed a very weak correlation with a (R^2) of 0.35, not allowing any trends to be deduced between them, as shown in Figure 3.

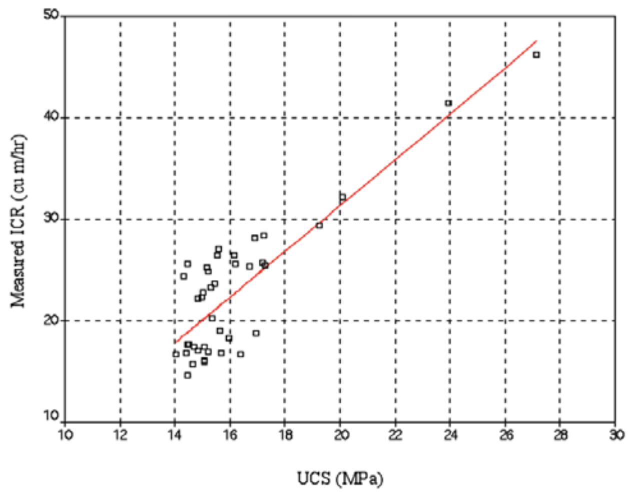

Figure 2—Relation between measured ICR and UCS of intact rock (R^2=0.71)

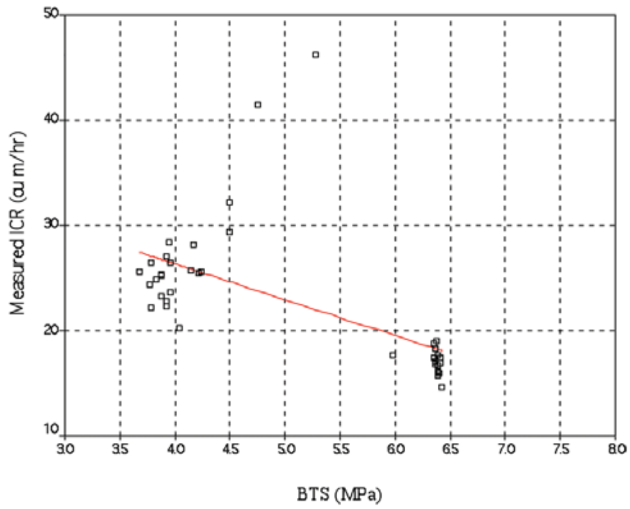

Figure 3—Relation between measured ICR and BTS of intact rock (R^2=0.35)

For rock formations showing a high degree of jointing and fracturing, such as conditions existing in the Tabas coal mine project, RQD would be expected to play a major role in machine performance; thus, the relationship between RQD and ICR was investigated as shown in Figure 4. As can be seen, although ICR increases as RQD increases, RQD is not enough to predict of the performance. Therefore, both intact rock and rock mass properties are required to be taken into account for an appropriate approach to more accurate and reliable performance prediction.

Rock mass brittleness analysis

As stated before, Equations [5], [6] and [7] are widely used strength ratios to quantify the brittleness index indirectly. In current study, these indices were computed with reference to the aforementioned equations and then were examined with respect to the measured ICR. Then the most appropriate brittleness equation with the highest correlation was chosen through analysis. Tables III, IV and Figures 5, 6, and 7 show these results.

As seen in Table IV, the ICR has the highest correlation with *BI2* (R^2=0.80). The correlation between ICR and *BI1* is less than the correlation between ICR and BI1 (R^2=0.72) and correlation between ICR and *BI3* is very poor (R^2=0.00). Therefore, *BI2* due to having the maximum correlation coefficient (R^2=0.81) among the others, was chosen to be used for rock brittleness index values to be incorporated in the model.

The rock mass brittleness index (RMBI) is then proposed by analysing geomechanical parameters from the database. RMBI is defined and proposed to attain a consistent correlation between rock properties and machine performance. The relationships between the rock mass brittleness index, the brittleness index (*BI2*) and RQD are found to be as follows:

$$RMBI = e^{\left(\frac{\sigma_c}{\sigma_t}\right)} \times \left(\frac{RQD}{100}\right)^3 \qquad [8]$$

By using Equation [6], the above equation can be written as follows:

$$RMBI = e^{BI2} \times \left(\frac{RQD}{100}\right)^3 \qquad [9]$$

where RMBI is the rock mass brittleness index, σ_c is the uniaxial compressive strength of rock (MPa), σ_t is the Brazilian tensile strength of rock (MPa), *BI2* is the brittleness index of intact rock, $BI2 = (\sigma_c/\sigma_t)$, and RQD is the rock quality designation of rock mass in per cent.

Performance prediction analysis

RMBI was applied to the database and then, the relation between RMBI and ICR was investigated. Consequently, the correlation is significantly improved (R^2=0.94), as shown in Figure 8. A summary of statistical model, analysis of variance and significance of the r-value and coefficients for the generated model are given in Tables V, VI and VII, respectively. The prediction model is as follows:

$$ICR = 30.75\, RMBI^{0.23} \qquad [10]$$

where ICR is the instantaneous cutting rate (m^3/h), and RMBI is the rock mass brittleness index.

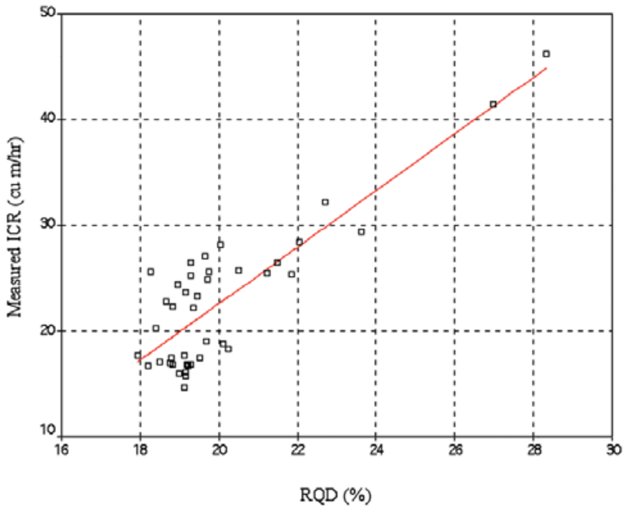

Figure 4—Relation between measured ICR and RQD (R^2=0.72)

Table III

Measured instantaneous cutting rate and computed brittleness indices

Case no.	Instantaneous cutting rate (m^3/h)	$BI1^a = \frac{(\sigma_c - \sigma_t)}{(\sigma_c + \sigma_t)}$	$BI2^a = \frac{\sigma_c}{\sigma_t}$	$BI3^a = \frac{\sigma_c \cdot \sigma_t}{2}$
1	22.4	0.59	3.91	28.04
2	25.3	0.59	3.91	29.39
3	24.8	0.60	3.98	29.10
4	23.8	0.59	3.90	30.51
5	23.3	0.60	3.95	29.72
6	22.6	0.59	3.83	29.41
7	27.0	0.60	3.97	30.61
8	25.7	0.59	3.93	26.57
9	25.7	0.58	3.82	34.34
10	20.2	0.58	3.80	31.04
11	28.4	0.60	4.06	35.26
12	24.5	0.58	3.80	27.05
13	26.5	0.59	3.93	30.79
14	25.5	0.61	4.15	35.54
15	41.6	0.67	5.04	56.83
16	45.6	0.67	5.14	71.71
17	32.1	0.63	4.47	45.26
18	16.8	0.37	2.20	44.92
19	17.4	0.41	2.37	47.76
20	17.0	0.39	2.27	45.87
21	17.1	0.40	2.33	47.22
22	17.6	0.39	2.29	47.13
23	16.8	0.42	2.46	49.86
24	16.7	0.44	2.56	52.28
25	16.1	0.40	2.36	48.21
26	17.6	0.39	2.27	46.41
27	16.1	0.40	2.36	48.21
28	16.8	0.41	2.37	48.73
29	14.6	0.38	2.25	46.39
30	19.2	0.42	2.45	49.81
31	17.8	0.42	2.42	43.17
32	15.8	0.39	2.29	46.88
33	18.6	0.46	2.67	53.89
34	16.9	0.42	2.47	49.94
35	18.2	0.43	2.51	50.81
36	26.5	0.62	4.26	30.58
37	25.2	0.62	4.31	32.32
38	28.4	0.63	4.37	33.96
39	25.2	0.61	4.10	36.44
40	29.6	0.62	4.28	43.25
41	22.3	0.59	3.82	29.45

a.Computed BI1, BI2, BI3

Table IV

Relation between measured ICR and *BI*1, *BI*2, and *BI*3

Cases	R	R^2	Adjusted R^2	Std. error of the estimation
ICR[a] vs. *BI*1[b]	0.85	0.72	0.71	3.62340
ICR vs. *BI*2[b]	0.90	0.81	0.80	2.99024
ICR vs. *BI*3[b]	0.01	0.00	-0.03	6.81421

a.Instantaneous cutting rate (m^3/h)
b.Brittleness indices; $BI1 = (\sigma_c - \sigma_t)/(\sigma_c + \sigma_t)$, $BI2 = \sigma_c/\sigma_t$, $BI3 = (\sigma_c \cdot \sigma_t)/2$

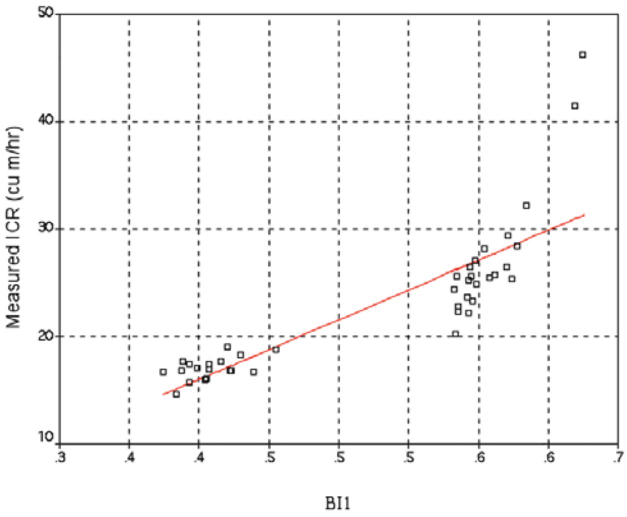

Figure 5—Relation between measured ICR and *BI*1 (R^2=0.72)

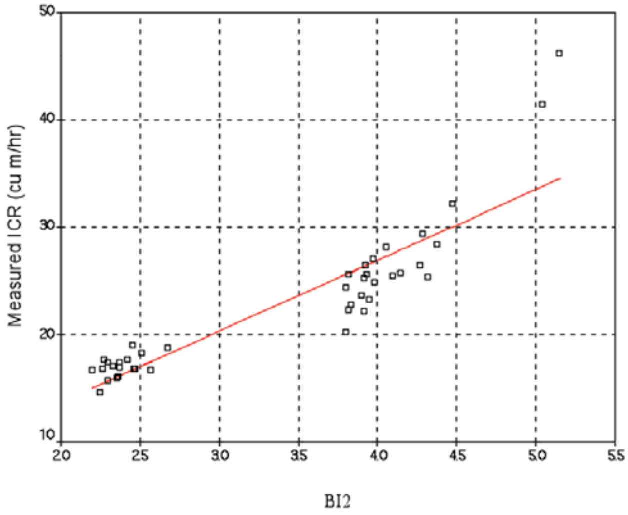

Figure 6—Relation between measured ICR and *BI*2 (R^2=0.81)

The comparison between the measured and predicted ICR (Equation [10]) is shown in Figure 9. Using the proposed equation, a reliable relationship between the predicted and the measured ICR were achieved with $R^2 = 0.94$. This model can be used to predict the ICR in the excavation of coal measures rocks with a medium duty roadheader fitted with an axial cutter head.

The RMBI can be identified as an index involving rock characteristics. Hence, the above methodology was applied for evaluating the interaction between pick (bit) consumption rate (PCR) and existing rock cutting condition. For this, the relation between RMBI and PCR was firstly investigated. Figure 10 shows the variation and relation of PCR with RMBI.

As seen in Figure 10, the correlation between PCR and RMBI is a bit low (R^2=0.67). Hence, further analysis and modification are required to reach a more accurate relationship between these two variables. After normalization by UCS and cutter head power, leading to introduce the pick consumption index (PCI), the scatter becomes smaller and the relationship shows significant improvement (R^2=0.79), as demonstrated in Figure 11. A summary of statistical model, analysis of variance and significance of the r-value and coefficients for the generated model are given in Tables VIII, IX and X, respectively. The predictive equations are as follows:

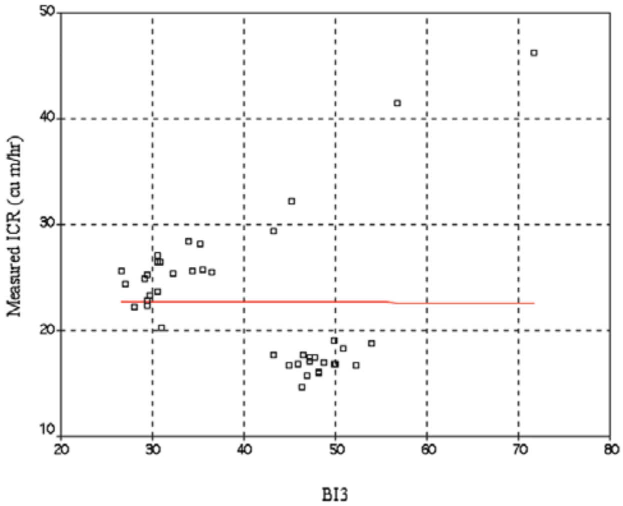

Figure 7—Relation between measured ICR and *BI*3 (R^2=0.00)

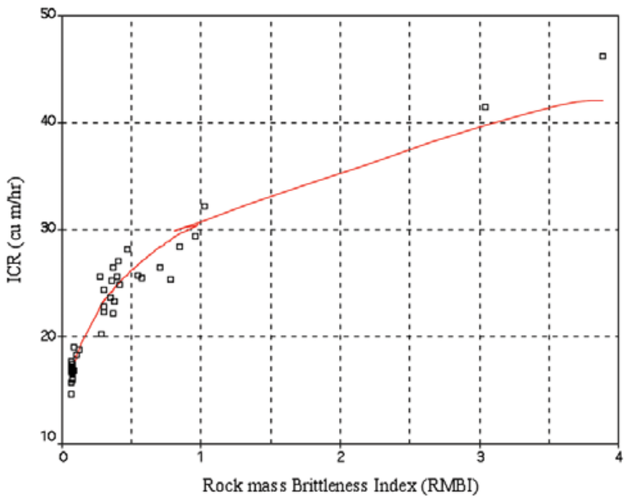

Figure 8—Relation between measured ICR and RMBI (R^2=0.94)

Table V

Summary of statistical model

Model type	R^a	R^2	Adjusted R^2	Std. error of the estimation
Power	0.97	0.94	0.94	0.06440

Dependent variable: measured ICR (m³/h)
a. Predictors: (constant), RMBI

Table VI

Analysis of variance for the generated model

Model	Variable	Sum of squares	df	Mean square	F	Sig. F
1	Regression residuals	2.6934198 0.1617366	1 39	2.6934198 0.0041471	649.47192	0.000[a]

Dependent variable: measured ICR (m³/h)
a. Predictors: (constant), RMBI

Table VII

Significance of r-value and coefficients for the generated model

Model	Variable	Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Std. error	Beta		
1	(Constant) RMBI	30.750579 0.230798	0.515510 0.009056	 0.971264	59.651 25.485	0.000 0.000

Dependent variable: measured ICR (m³/h)

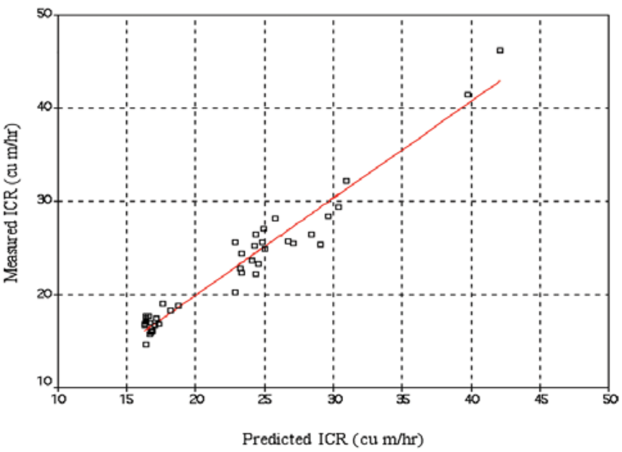

Figure 9—Linear regression between measured ICR and predicted ICR (R^2=0.94)

$$PCI = e^{RMBI} \times \left(\frac{UCS}{P}\right) \quad [11]$$

$$PCR = 45.10 PCI^{-0.15} \quad [12]$$

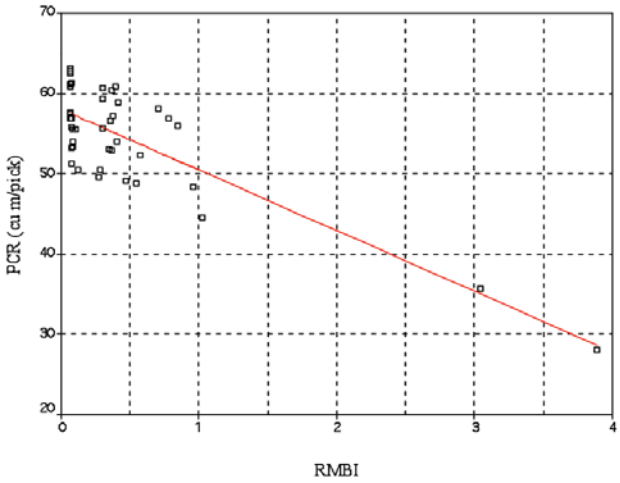

Figure 10—Plot of variation between PCR and RMBI (R^2=0.67)

Table VIII

Summary of statistical model

Model type	R^a	R^2	Adjusted R^2	Std. error of the estimation
Power	0.89	0.79	0.78	0.06898

Dependent variable: measured PCR (m³/pick)
a. Predictors: (constant), PCI

Table IX

Analysis of variance for the generated model

Model	Variable	Sum of squares	df	Mean square	F	Sig. F
1	Regression residuals	0.70811510 0.18559170	1 39	0.70811510 0.00475876	148.80239	0.000

Dependent variable: measured PCR (m³/pick)
a. Predictors: (constant), PCI

Table X

Significance of r-value and coefficients for the generated model

Model	Variable	Unstandardized coefficients		Standardized coefficients	t	Sig.
		B	Std. error	Beta		
1	(Constant) PCI	45.103481 -0.153443	0.826570 0.012579	 -0.890132	54.567 -12.198	0.000 0.000

Dependent variable: measured PCR (m³/pick)

where PCI is the pick consumption index, RMBI is the rock brittleness index, PCR is the pick consumption rate (m³/pick), UCS is the rock uniaxial compressive strength (MPa), and P is the cutter head power (kW). In the above equation, P is considered to be 82 kW (cutter head power of DOSCO MD 1100 roadheader).

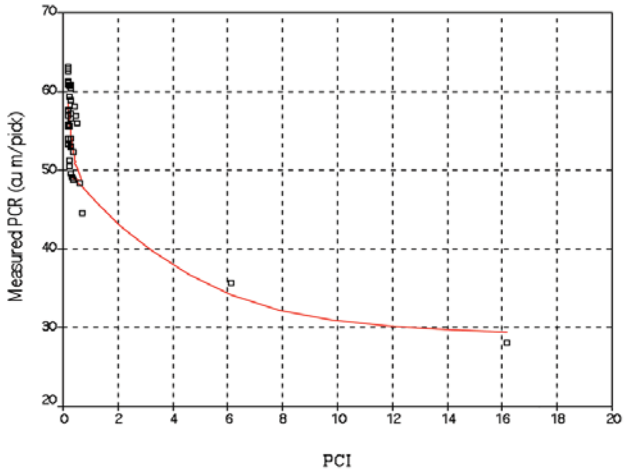

Figure 11—Relation between measured PCR and PCI (R^2=0.79)

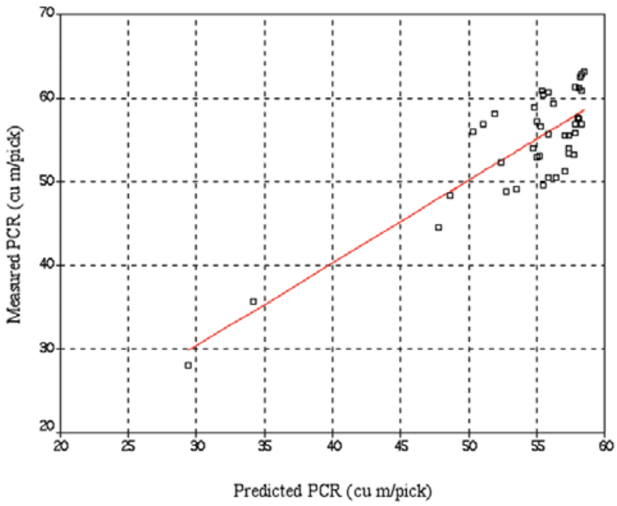

Figure 12—Linear regression between measured PCR and predicted PCR (R^2=0.71)

Similarly, the comparison between the measured and the predicted PCR is given in Figure 12 for each cutting case. Using Equation [12] for prediction of PCR, a reliable relationship between the predicted and the measured PCR was obtained with R^2 = 0.71.

Conclusions

Primarily, a database of geomechanical parameters and machine performance was established from the DOSCO roadheaders working in the Tabas coal mine tunnels. The evaluation and analysis of the established database yielded new sets of equations which can be used to predict the instantaneous cutting rate (ICR) and pick consumption rate (PCR). With this, the rock mass brittleness index (RMBI) was introduced as an index which can be used to relate the intact and rock mass characteristics to the machine performance. A good relationship was found to exist between ICR and RMBI with a high correlation (R^2=0.94). The results also showed that a fair correlation (R^2=0.67) exists between pick consumption rates (PCR) and RMBI. However, by the introduction of a pick consumption index (PCI) in the equation, a much better correlation (R^2=0.79) was then reached. The comparison between the measured and predicted ICR and PCR show that a good correlation exists between them. Therefore, these new models can successfully be used to predict the performance of roadheaders.

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